Principles for Designing Compliant Multifunctional Wing Structures with Integrated Solar Cells for MAVs

Prof. Hugh A. Bruck
Prof. Sayandra K. Gupta
Department of Mechanical Engineering
University of Maryland
College Park, MD

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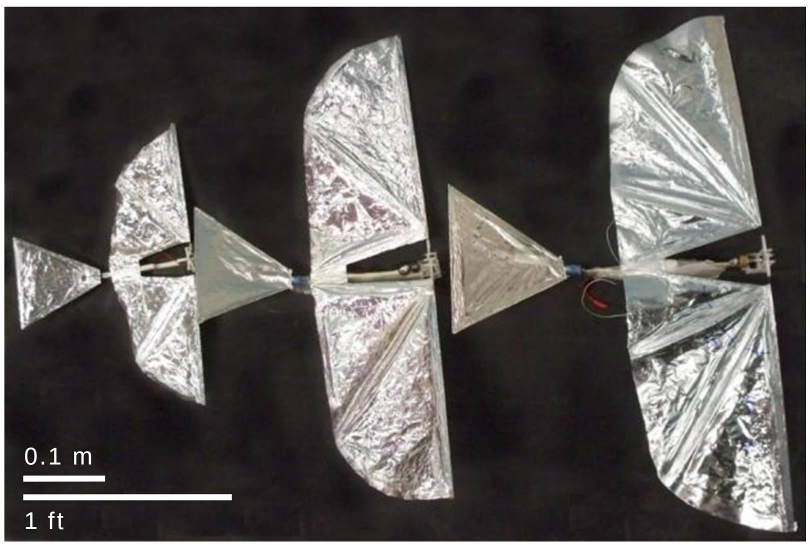
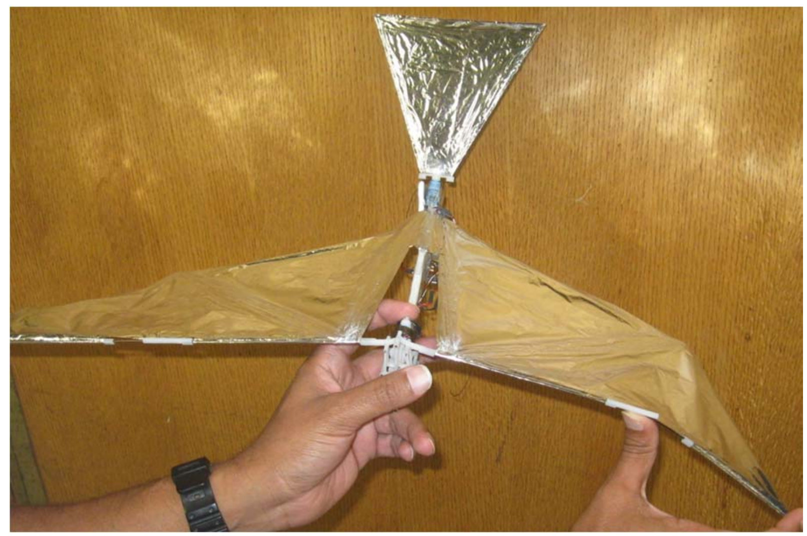
Motivation:
Flapping Wing MAVs

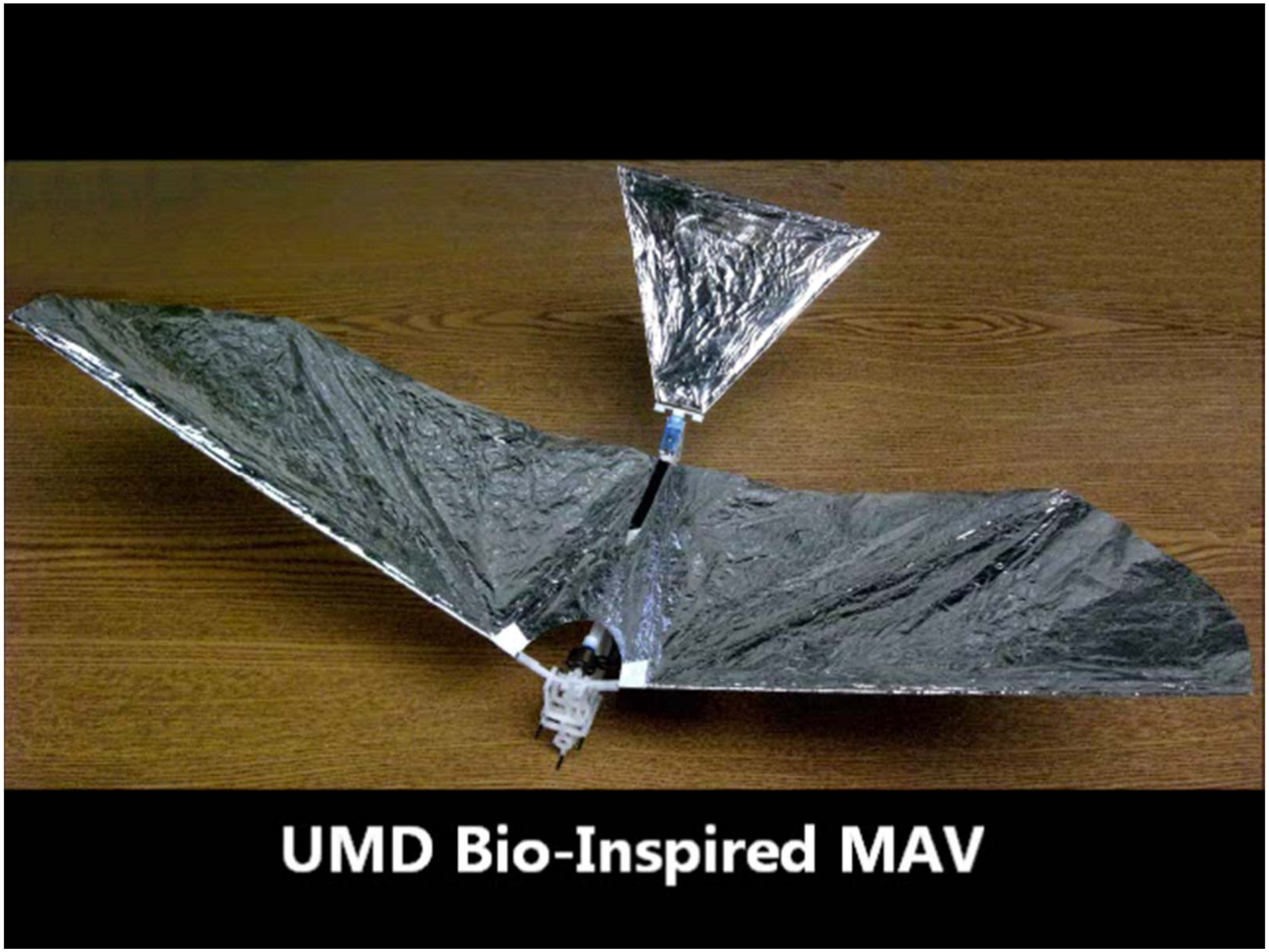
- Flapping wing MAV platforms are expected to be highly maneuverable and quiet
- We have been designing and building Flapping Wing MAVs for 8 years
  - Increase payload capacity
  - Increase drive mechanism efficiency to reduce power consumption
  - Reduce weight to increase time-of-flight





Micro Air Vehicles developed in
Advanced Manufacturing Lab, UMD

Flapping Wing MAVs: *Previous Accomplishments at UMD*

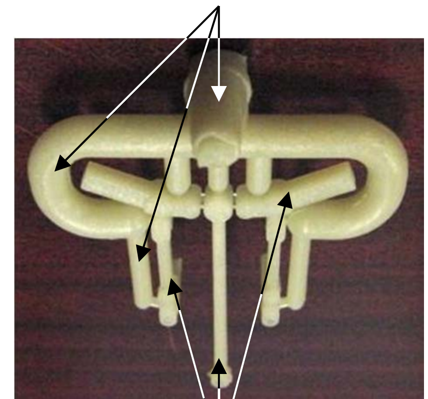


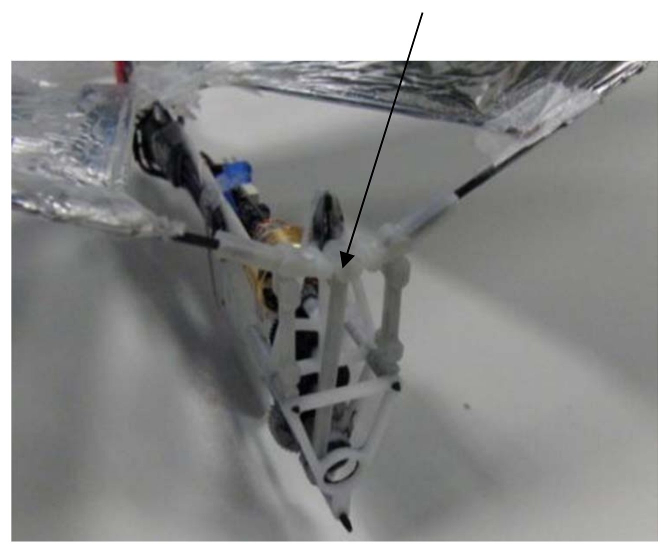
Enabling Technology: *In-Mold Assembly*

- In-mold assembly process for realizing multi-material articulated structures
- Introduce multiple materials in the mold sequentially
  - Change mold cavity between different molding stages
- Perform assembly and fabrication inside the mold
  - Mold acts as fabrication tool and assembly device
- Eliminate post-molding assembly
  - Attractive in markets where labor cost is high

This two degree of freedom gimbal comes out of mold fully assembled (Work done in AML)

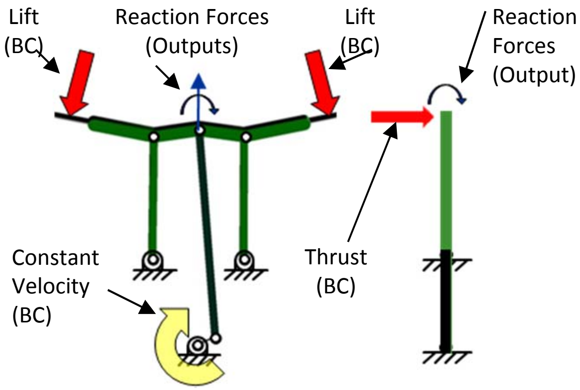
[Bejgerowski, Gupta, Bruck, *IJAMT* (2011)]

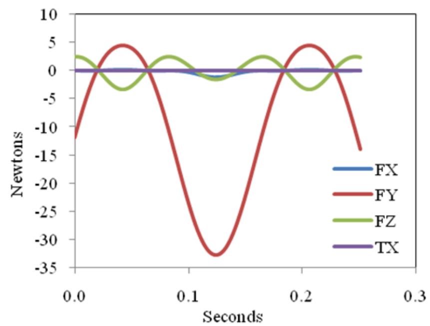




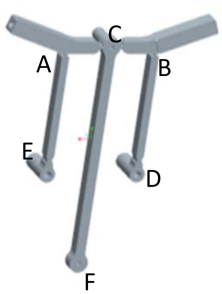
Enabling Technology:
Simulation Based Computational Synthesis for Design Space Exploration and Parametric Optimization

- Mechanism Design Analysis:
  - Kinematic analysis (ADAMS)





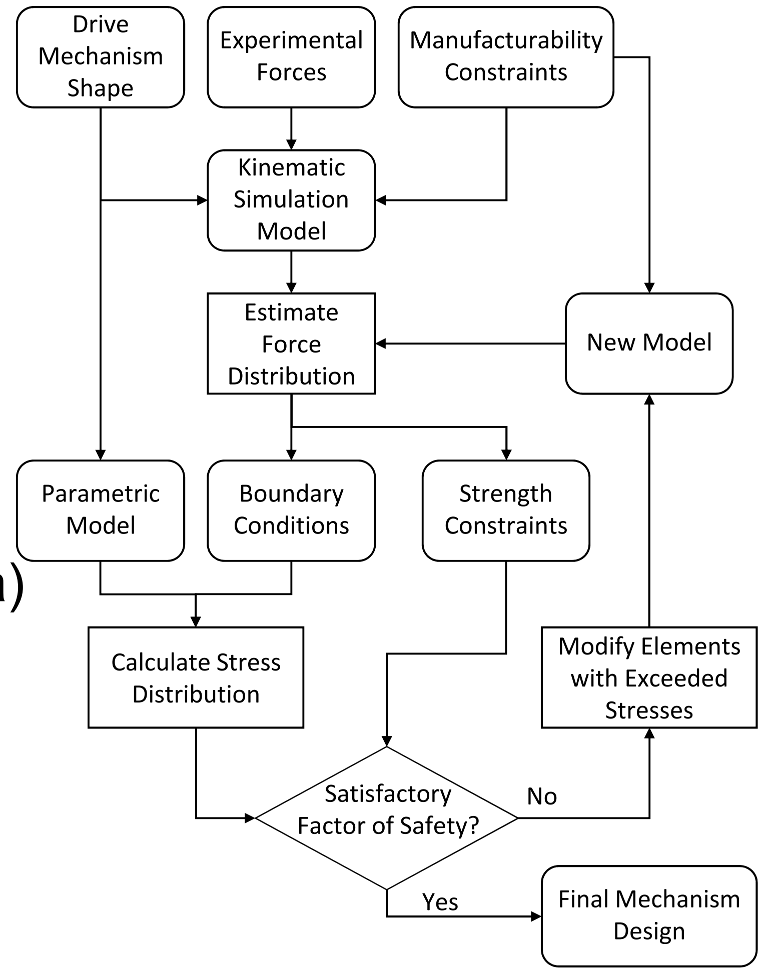
  - Finite element analysis (ProMechanica)



Component	*Applied to*	*Unit*	*Value*
X	A	*N*	-1.159
Y	A	*N*	-32.767
Z	A	*N*	-1.559
X	C	*N*	0.026
Y	C	*N*	31.141

- Results:

Variable	*Unit*	*Value*
Rocker thickness	*mm*	2.1
Rocker breadth	*mm*	2.5
Wing arm thickness	*mm*	2.5
Wing arm breadth	*mm*	5.1
Hinge encapsulation thickness	*mm*	7.5
Hinge encapsulation breadth	*mm*	5.0

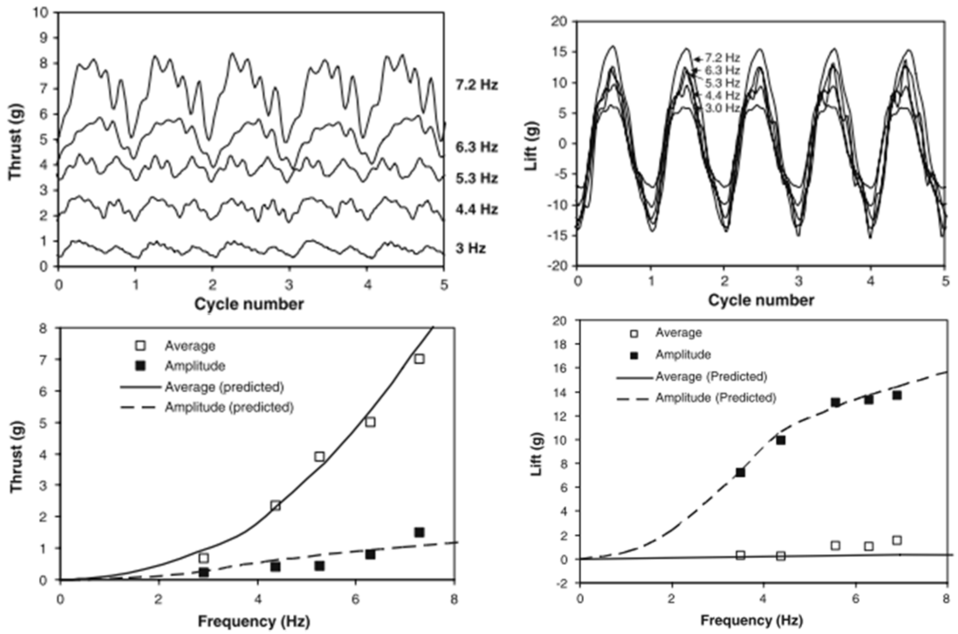


Mechanism Design Optimization

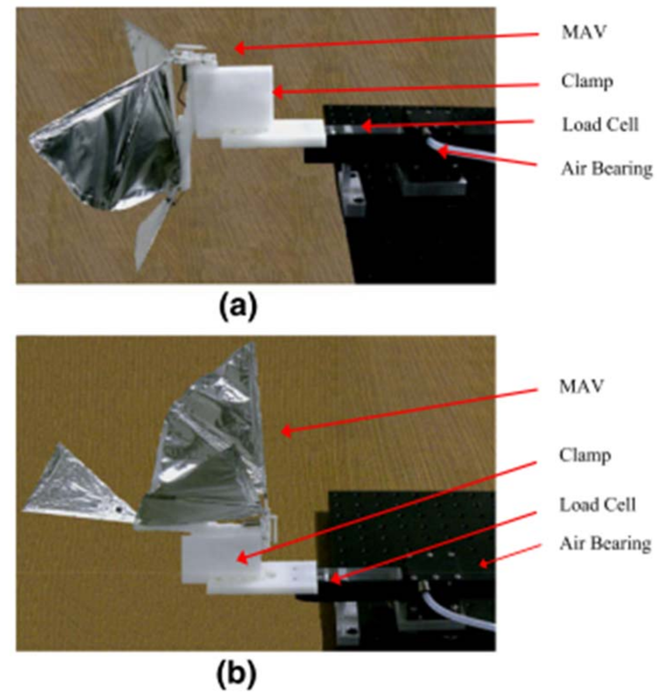
[Bejgerowski, et al, *JMD* (2009), Bejgerowski, Gupta, Bruck, *JMD* (2009)]

Enabling Technology: *Wing Characterization*

- Advanced wing characterization for understanding forces and deformation



(top) Cyclic Variation of Lift and Thrust,
(bottom) Variation with Flapping Frequency



Test Stand for Measuring:
(a) Lift & (b) Thrust

[Mueller, Bruck, Gupta, *Exp. Mech.* (2010)]

Current Challenges

- Flapping Wing MAVs can not fly more than 40 minutes because of payload constraints
- Need platforms that can harvest energy while flying or resting to increase time-of-flight
- Energy harvesting technologies like *Solar Cells* can induce a tradeoff in power consumption due to increases in mass, stiffness, and wing area
- Effective integration requires understanding of mechanics principles that govern tradeoffs in order to enhance performance and increase time-of-flight

Solution: *Multifunctional Compliant Wings*

- Energy harvesting
  - Technologies such as flexible Solar Cells (SCs) can be integrated into compliant MAV wings
- Energy storage
  - Energy from SCs can be directed to battery structures integrated into body of MAV
- Thrust production
  - Need to mitigate effects of SC integration on compliance
- Lift generation
  - Needs to be able to fold wings to increase static lift
- Maneuverability
  - Need to account for SC effects on control of wings

Research Goals & Anticipated Impact

Research Goals

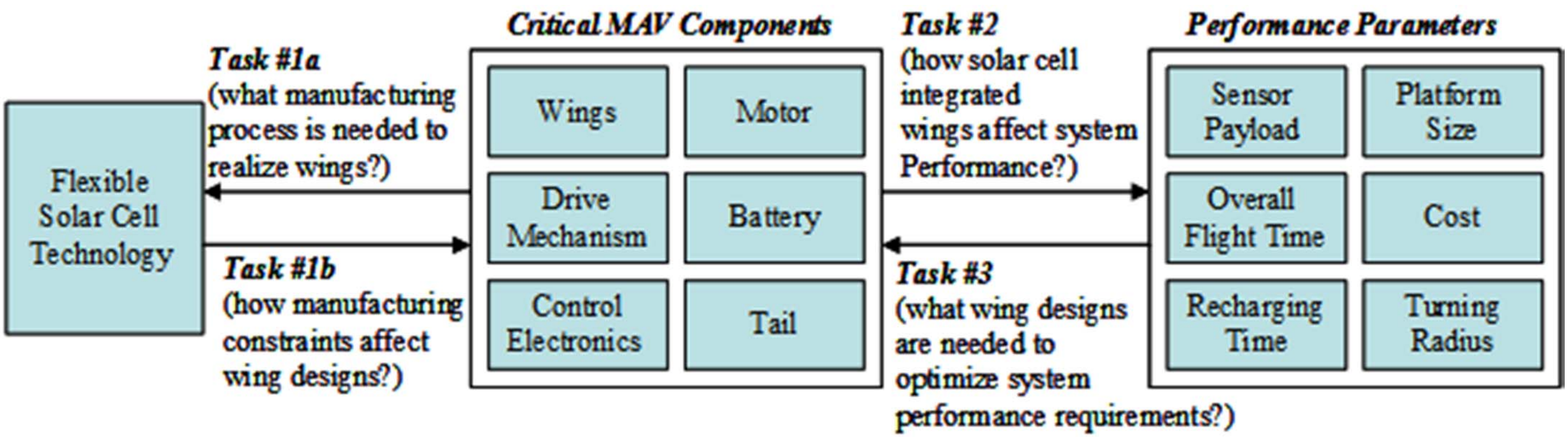
- Develop new compliant multifunctional wing structures for flapping MAVs
- Improve the time-of-flight for flapping MAVs through integration of solar cells
- New models for effects of integrating solar cells on compliance and performance in order to define a new multifunctional performance index for optimizing wing design

Anticipated Impact

- Compliant multifunctional wing structures have the potential to provide flapping MAVs with infinite flight capability
- Characterizing and modeling the mechanics of these wing structures will enable general design principles to be developed for flapping MAVS

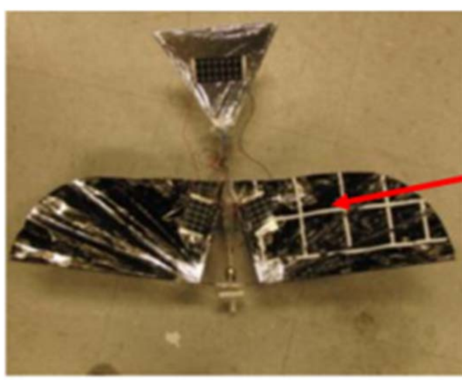
Proposed Research Approach

Experimental mechanics-based system design approach to integrating SCs into compliant wings for MAVs for improving time-of-flight through trade-off in energy harvesting and consumption



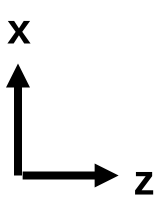
Solar Cell Integration into Compliant Wing Structures

- Use pre-packaged flexible Solar Cells (SCs) on existing wing structures
  - Parasitic Mass and Stiffness
- Size and distribution of SCs can be varied
- Mechanics of SC integration can vary with wing spar configurations and bird sizes

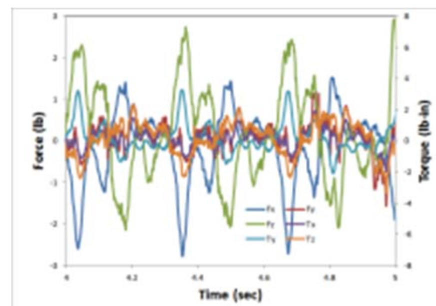


Experimental:
Lift and Thrust Measurements

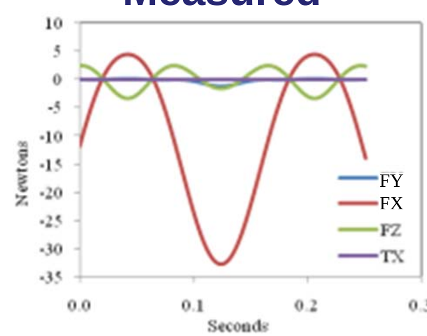
- A test stand was developed to measure lift and trust forces generated by the MAV, as well as torque
- The MAV is mounted directly to a 6 DOF load cell from ATI in order to measure all forces and torques simultaneously
- Can compare measured with designed forces and torque to resolve any asymmetries due to wing construction or in the flapping motion



6 DOF Load Cell



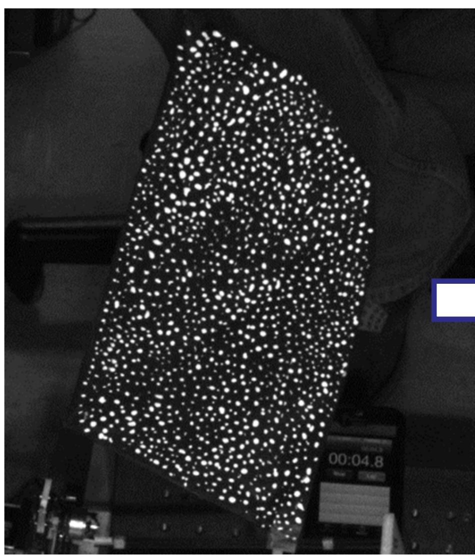
Measured



Designed

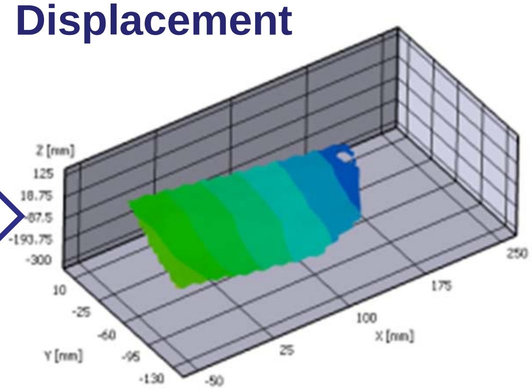
Experimental:
3-D Digital Image Correlation (DIC)

- Digital Image Correlation is an optical method [Bruck, Sutton, et al, *Exp. Mech.* (1989)] developed to measure 2D or 3D deformations on an object surface under real loading conditions, which can be viewed as an "Optical Finite Element Analysis"
- Actual displacement is continuously measured and the Lagrangian strain tensor is available at every point on the specimen's surface

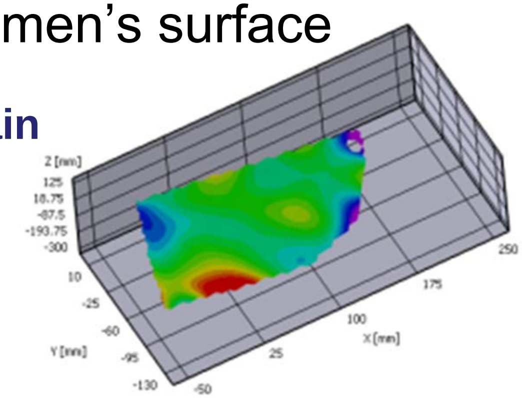


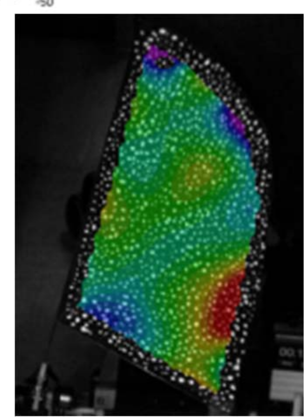
Wing w/speckle pattern for DIC

Out-of-plane Displacement

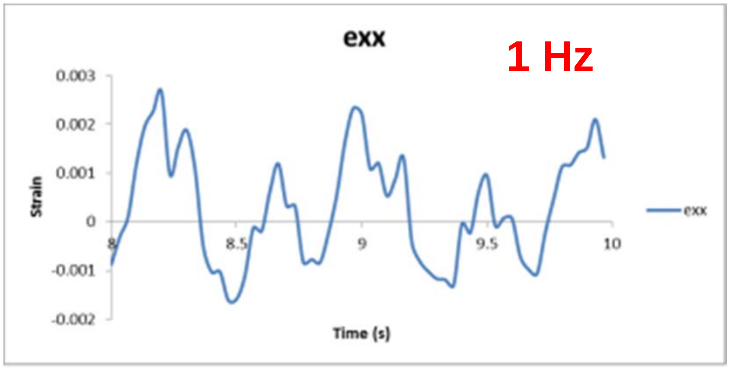


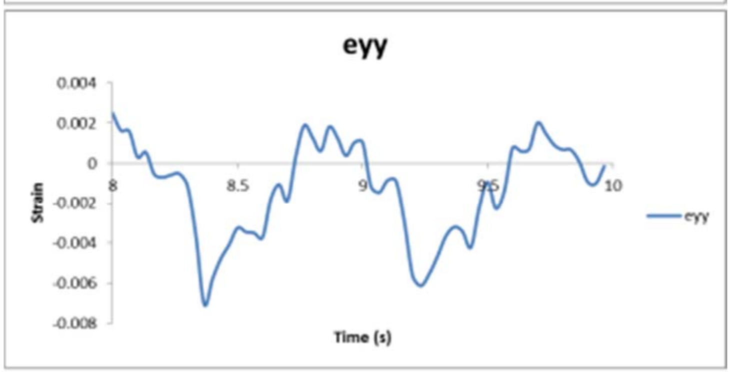
In-plane Strain

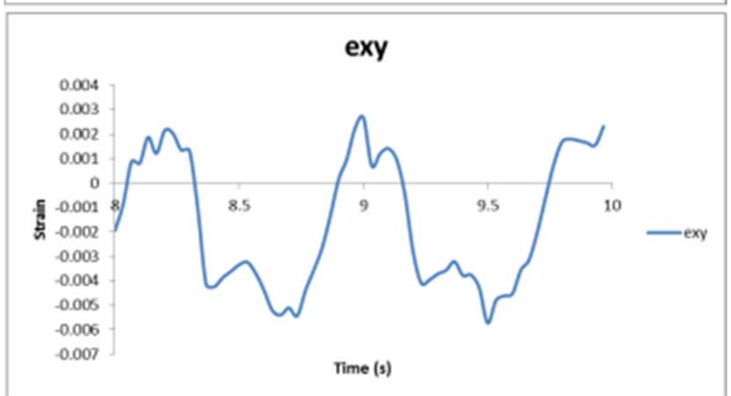


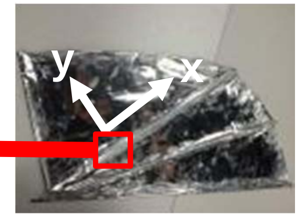


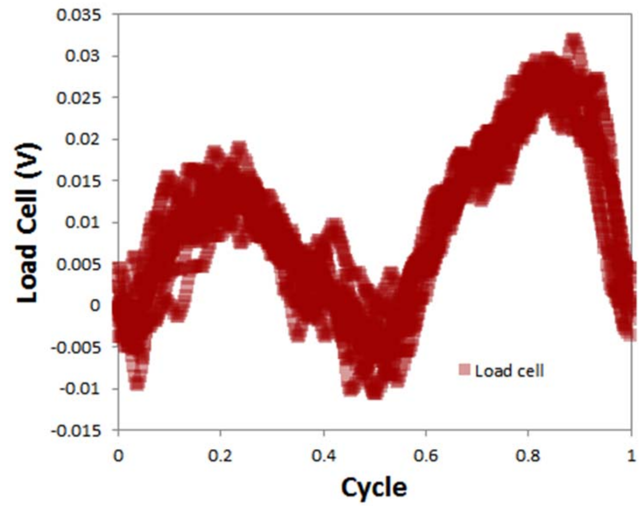
Comparison of 3-D DIC with Thrust Measurements





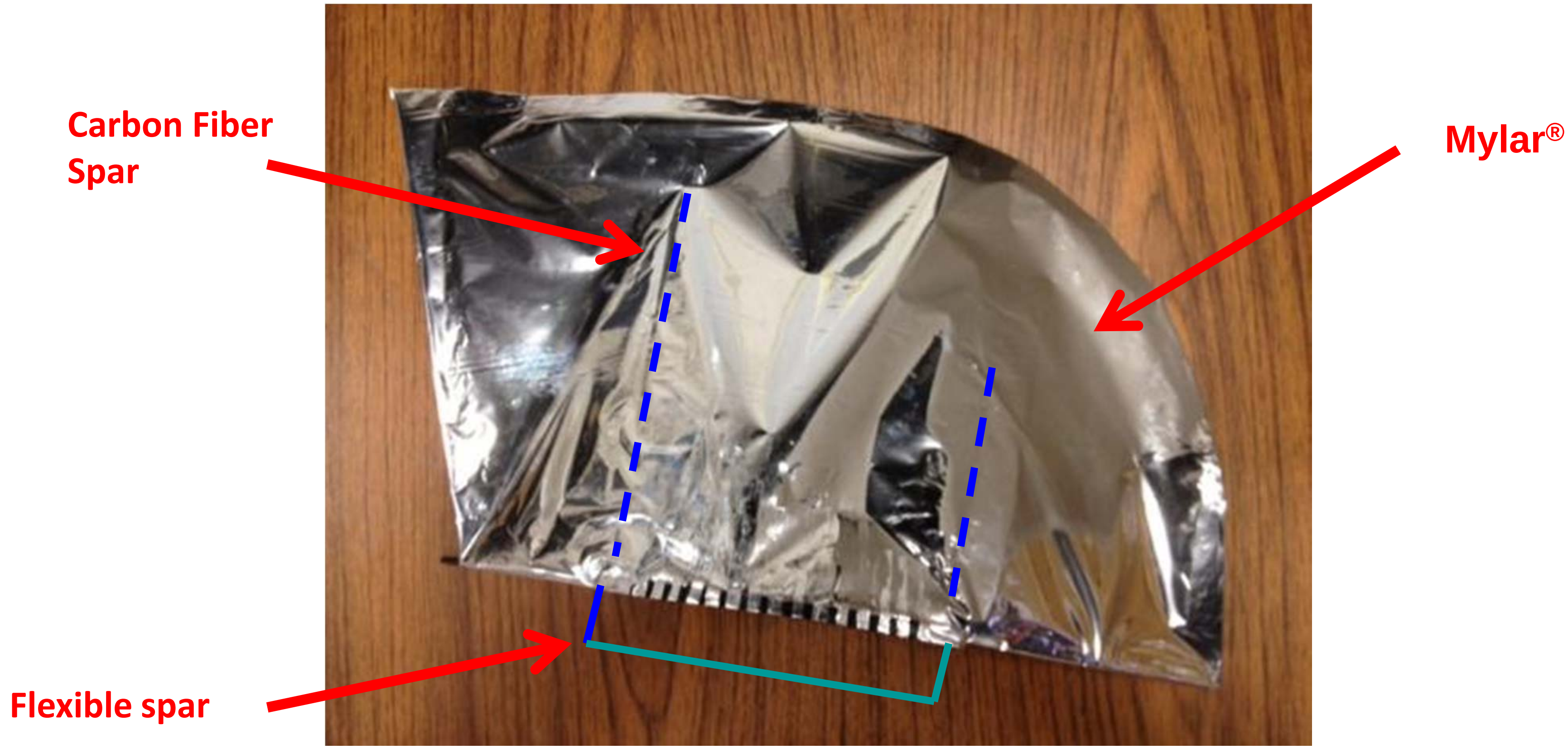






Transformed DIC strains along direction of spar correlated most directly with thrust measurements obtained from test stand

Compliant Front Spar Wing

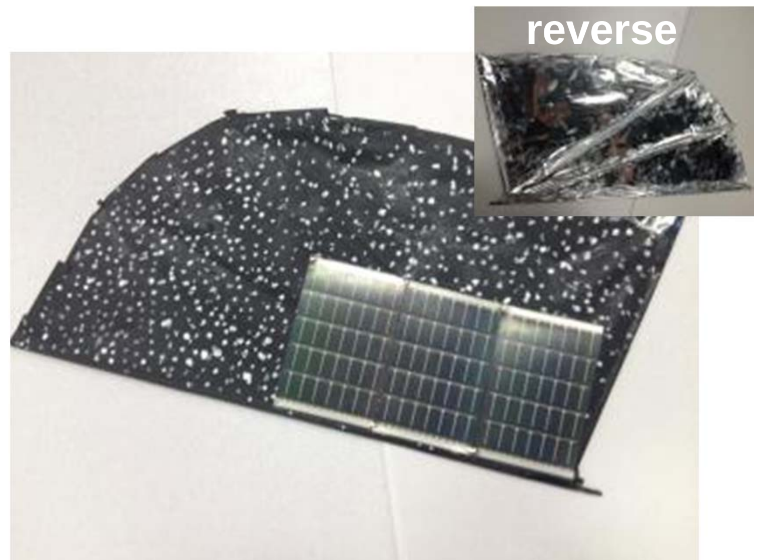


- Composed Mylar® wing material
- Flexible spar section fixed between two carbon fiber rods
- Two additional carbon fiber rods support the wing

Solar Cell (SC) Integration into Wings

3 OEM Solar Cell Modules

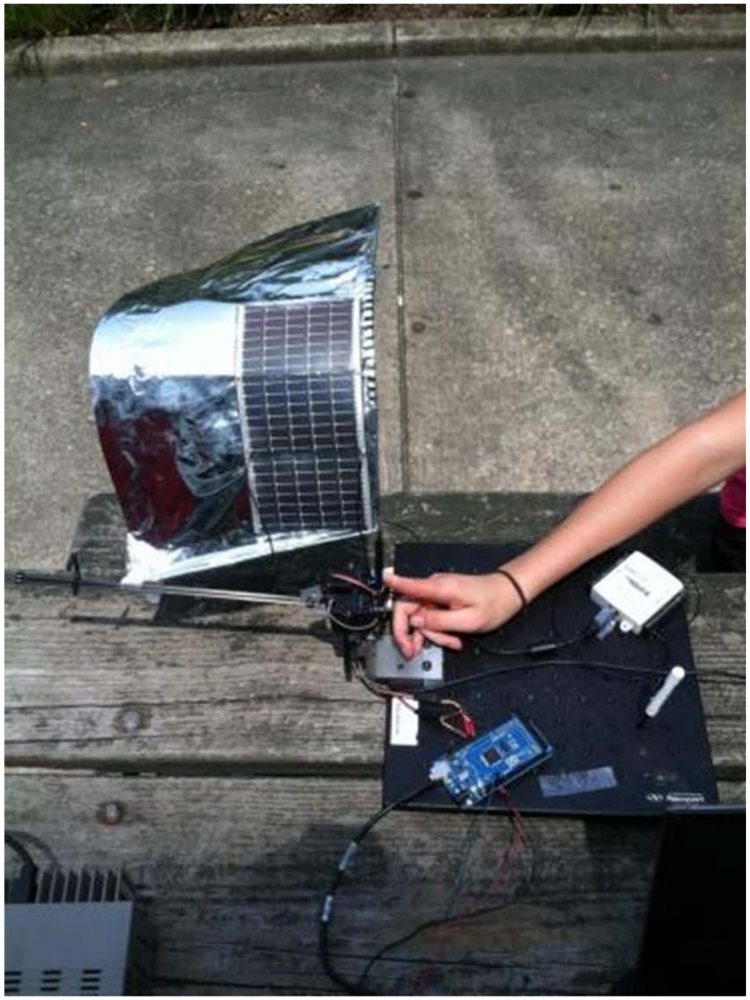
Compliant Front Spar



Stiff Front Spar

SCs can be aligned in parallel to maximize current, and coverage can be varied

Characterization of MF Wing Performance



Outdoor testing of integrated SCs on regular front spar wing (left) and compliant front spar wing (right)

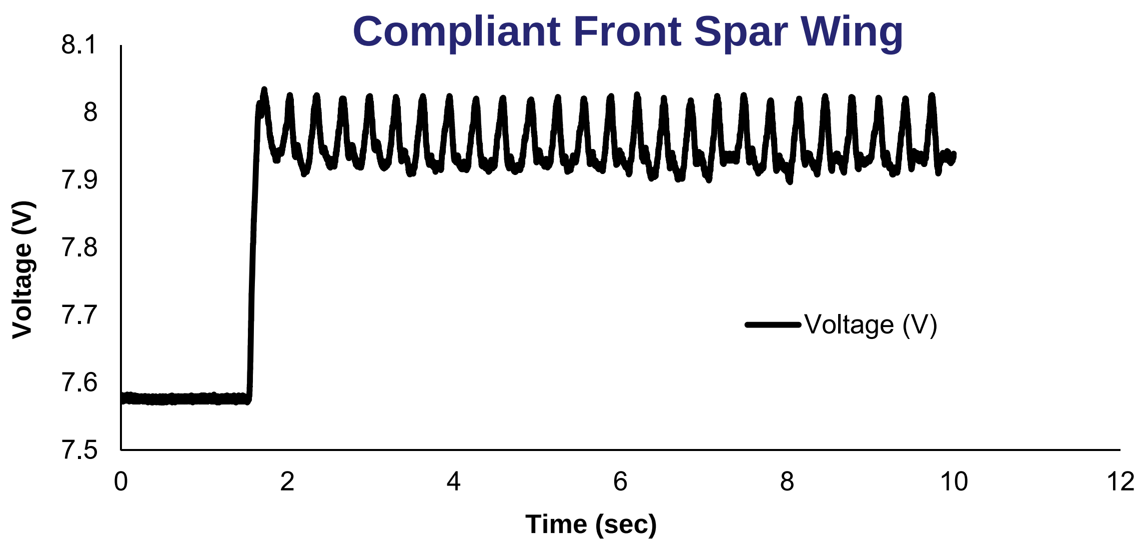
Stiff vs. Compliant Front Spar: *3 Hz flapping frequency*

Stiff Front Spar

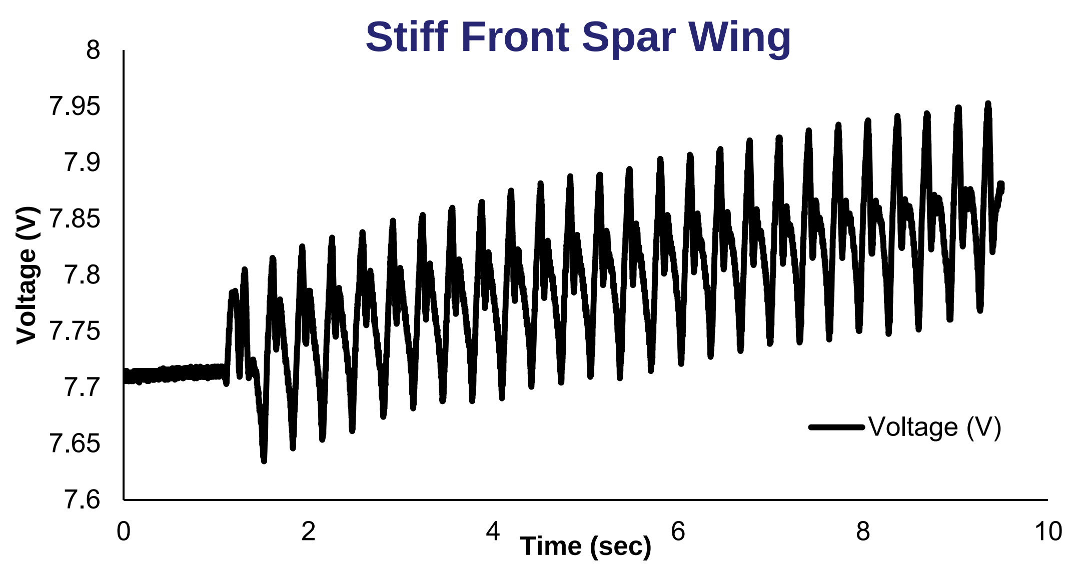
Compliant Front Spar

Significant differences in shapes during flapping for compliant front spar relative to stiff front spar are easily discerned from high speed videos

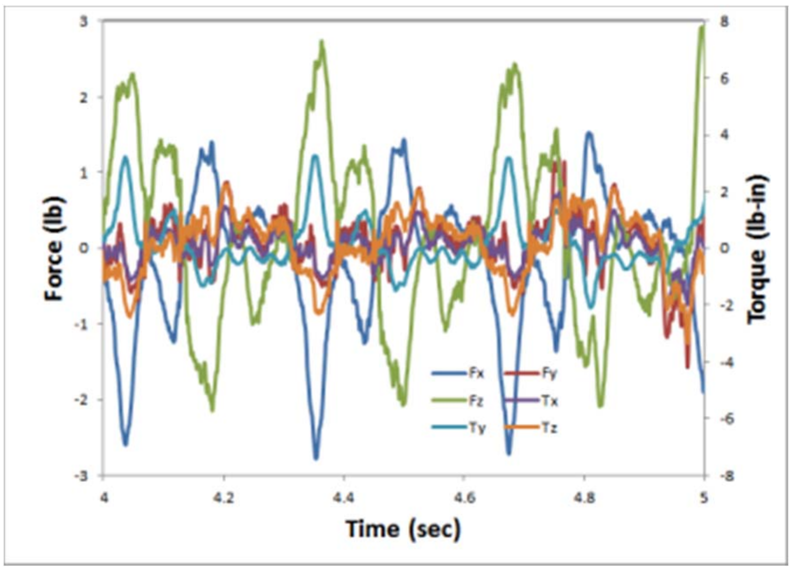
SC Performance while Flapping



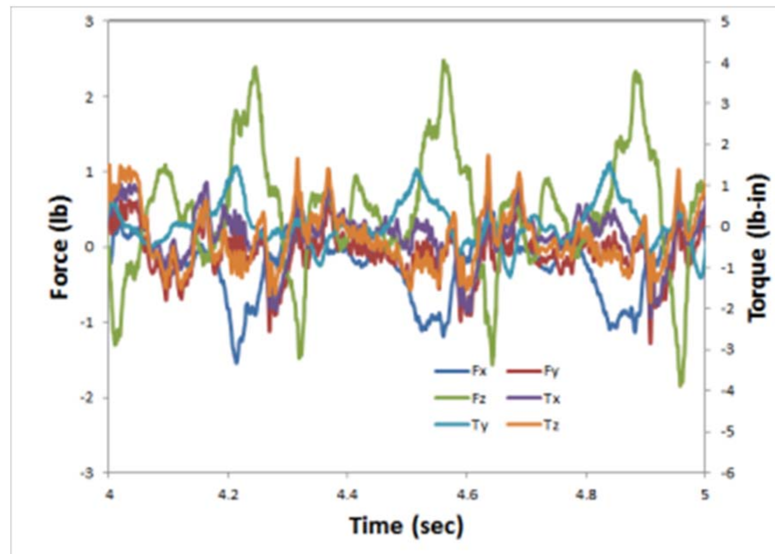
Compliant MF wings exhibit more stable and enhanced energy harvesting capability



Load Cell Results



Stiff Front Spar



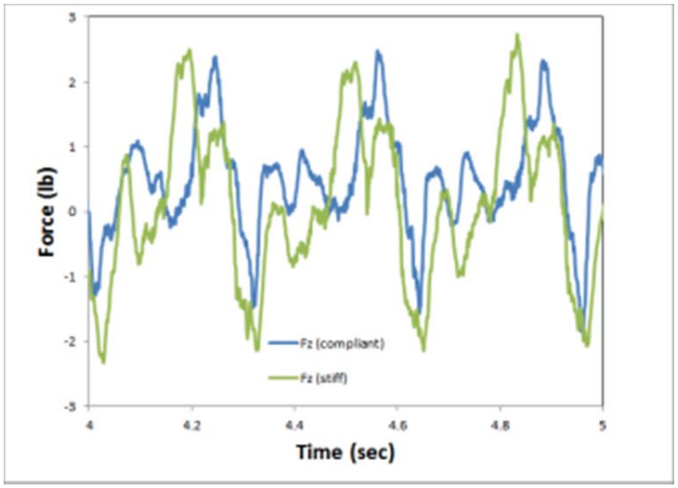
Compliant Front Spar

+z: thrust direction
-x: lift direction

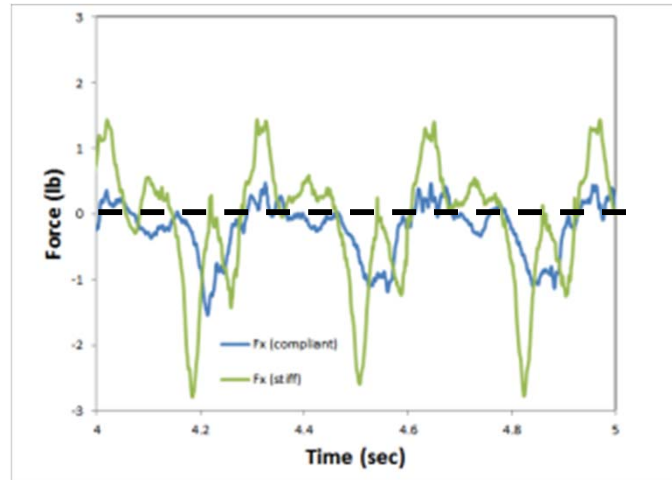
Load cell measurements indicate very little asymmetry in flapping performance for both stiff and compliant front spars

Stiff vs. Compliant Front Spars: *Thrust and Lift*

Thrust



Lift

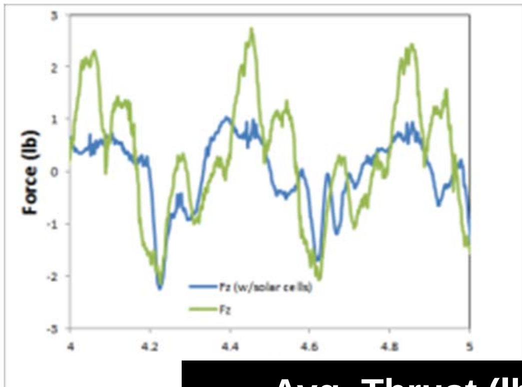


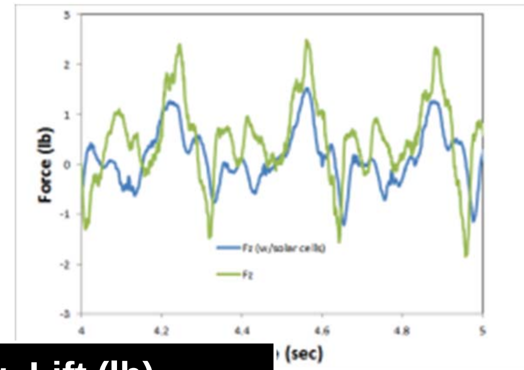
Avg. Thrust (lb)		Avg. Lift (lb)	
Stiff	Compliant	Stiff	Compliant
0.24	0.48	0.22	0.25

- **Compliant spar generates 100% more thrust**
- **Downward lift component is eliminated with compliant front spar with slight increase overall**

Effects of SC integration

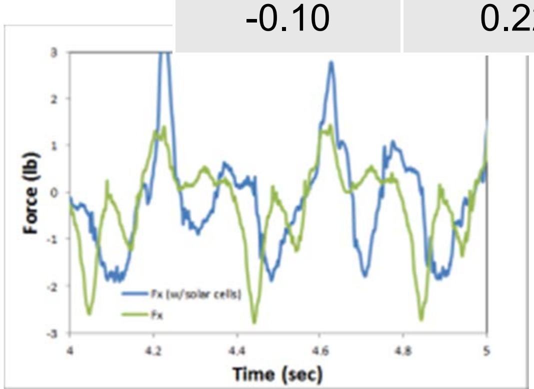
Stiff Front Spars | Compliant Front Spars

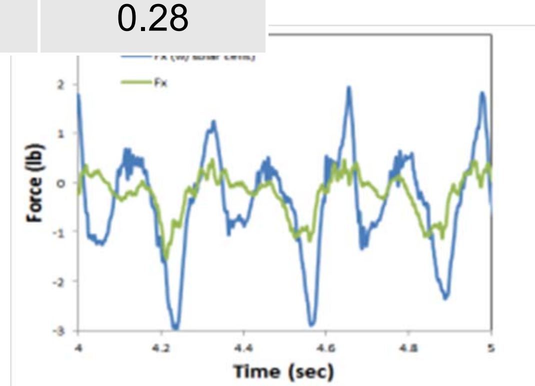




Thrust

Avg. Thrust (lb)		Avg. Lift (lb)	
Stiff	**Compliant**	**Stiff**	**Compliant**
-0.10	0.22	0.21	0.28



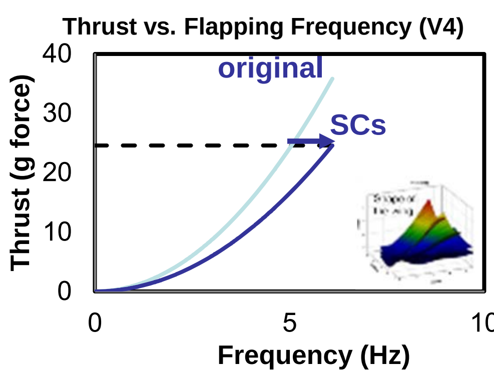


Lift

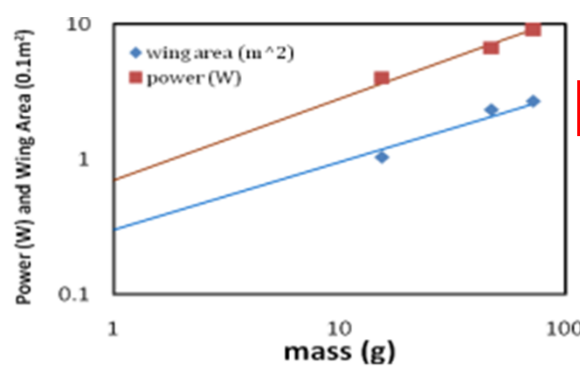
- **SC integration significantly decreases thrust/negligible lift change**
- **Compliant front spar has 3% more lift than stiff front spar**

Mechanics of SC Integration into Compliant Wing Structures

- Integration of Solar Cells (SCs) can reduce thrust and lift generation
  - Increases inertial mass of wing
  - Stiffens wing
- Effects of SCs vary with mass of bird and size of wings
- Need to relate benefits of energy harvesting to detrimental effects on flapping performance of compliant wing structures to develop *multifunction performance index*



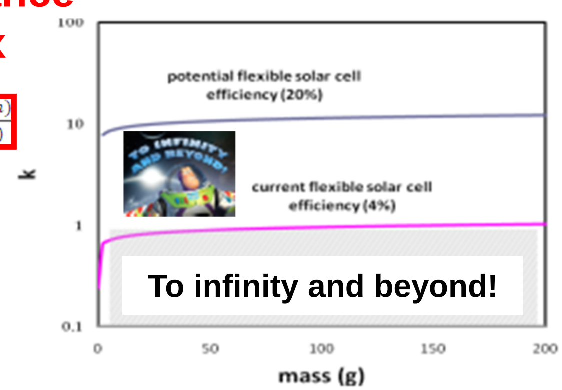
Effects of SCs on Flapping Performance



Variation of UMD MAV Characteristics with Mass

Multifunctional Performance Index

$$k_c = \frac{S_f}{P_o} = \frac{cQA(m)}{P_o(m)}$$



Multifunctional Performance Analysis

Conclusions

- Commercial SCs are being integrated into compliant MAV wings for energy harvesting
- Impact of SCs on MAV thrust generation is being characterized and related to shape constraint using 3D DIC
  - Can develop a new *multifunctional performance index* for optimizing performance
- The effects of compliant versus stiff front spars have been characterized use 6 DOF load cell
  - Can determine benefits of compliant front spars in generating more lift to offset weight of SCs
  - Can reduce power requirements by reducing flapping frequency

FY13 Efforts

- Characterize flapping frequency effects on MF wings
- Conduct extensive 3D DIC characterization of MF wings
- Develop mechanics model for MF wings
- Conduct time-of-flight tests
- Use mechanics model to modify design synthesis of MF wings
- Re-design MF wing to enhance time-of-flight